DOI: 10.18372/2310-5461.40.13279

UDC 629.7.03:681.5.03 (045)

N. V. Olali, Ph.D, Assoc. Prof. in the Dep. of Mathematics / Comp. Sc.,
Niger Delta University, Nigeria
orcid.org/0000-0001-8962-4538
e-mail: dr.nataliyagrishchuk@mail.com;

M. O. Olali, Ph.D, Assoc. Prof. in the Dep. of Mechanical / Marine Eng.,
Niger Delta University, Nigeria
orcid.org/0000-0001-8962-4538
e-mail: mikolali@hotmail.com

THE SURGE IDENTIFYING DEVICE IN COMPRESSORS OF AVIATION GAS-TURBINE ENGINES

Introduction

Modern aviation gas-turbine engines (GTE) are complex thermal machines, which consist of a large number of the connected systems and devices to which requirements of obtaining extreme values of parameters in the set service conditions are imposed (the minimum specific fuel consumption on the nominal mode, the maximum draft at take-off, etc.).

These factors lead to permanent complication of designs of modern GTE, emergence of new systems and devices — adjustable guide devices, air bleed valves, adjustable cooling systems of the turbine etc. Such complications of a design cause a possibility of fluctuations of separate parameters, and also a possibility of influence of fluctuations in one systems on work of other systems and emergence of multi-frequency fluctuations in GTE.

The peculiarity of all these modes is existence of periodic components.

Problem statement

The results of researches, presented in [1, p. 217], [2, p. 502], [3, p. 112], [4, p. 128], show, that surge phenomena in GTE lead to loss of power, and are followed by growth of temperature of gases in front of the turbine and increase of vibration level as a result of big amplitudes of pressure pulsations and mass expenses on a path of the engine.

The possibility of emergence of these phenomena is a serious obstacle on the way of increase in reliability of GTE, including safety of flights in general. Short-term loss of power in case of a surge on one of the engines for the multiple-motor plane or even for the single-motor plane in case of sufficient to run the clearance rate does not lead to a catastrophic situation [1, p.218].

However growth of temperature and increase of vibration level can lead to a burnout of nozzle diaphragms of the turbine and other breakages [2, p. 503]. Operating experience [2, p. 502], [3, p. 112], [4, p. 128] shows that especially dangerous for the engine is an inadmissibal temperature increase of gases in front of the turbine.

To increase GTE marginal stability regulation of the guide devices of the compressor, bleed from separate compressor stages, adjustable dispensing of fuel supply on the modes of start, throttle of throttling, etc are used.

These measures reduce probability of emergence of the surge phenomena, but can't serve as a guarantee of their elimination as the surge can be a consequence of failures in the systems intended for the prevention of failures.

Besides, increase in marginal stability leads to considerable decrease in compressor efficiency and, respectively, profitability of GTE [4, p. 130]. Therefore it is expedient to allow small emergence of a surge, but to equip GTE with emergency systems of surge protection and to provide the maximum profitability of engines [6, p. 15].

Efficiency of usage of such systems significantly depends on an identification method, whis is put in its principle of operation. In this regard the identification method is of special interest. It uses orthogonal expansion of pulse transitional functions in a row on Walsh functions.

In this case the possibility of false operation of signaling devices of a surge owing to sharp changes of an operating mode of GTE is eliminated, and also dimension of space of diagnostic signs in comparison with diagnosing on the basis of counting of the studied process is reduced [1, p. 219]. Thus, we will formulate a research problem in the form of justification of applicability of an identification method on Walsh functions and develop the algorithmic providing in systems of recognition of the surge and pre-surge phenomena in aviation GTE.

Properties of Walsh orthogonal functions

We will consider the main properties of Walsh orthogonal functions which we will use at a statement of the offered identification method. Walsh functions belong to the class of piecewise and continuous orthogonal functions [3, p. 113] which has made a basis for creation and development of the sequent analysis, that is the research of processes by means of not sinusoidal functions.

Visually the system of Walsh functions is brought out of system of Rademakher functions. Rademakher function $r_m(t)$ with an index m has a form of sequence of rectangular impulses and contains 2^{m-1} periods on an interval [0,1], accepting values +1 or – 1 (Fig. 1).

The exception is made by function $r_0(t)$ which has a form of a single impulse.

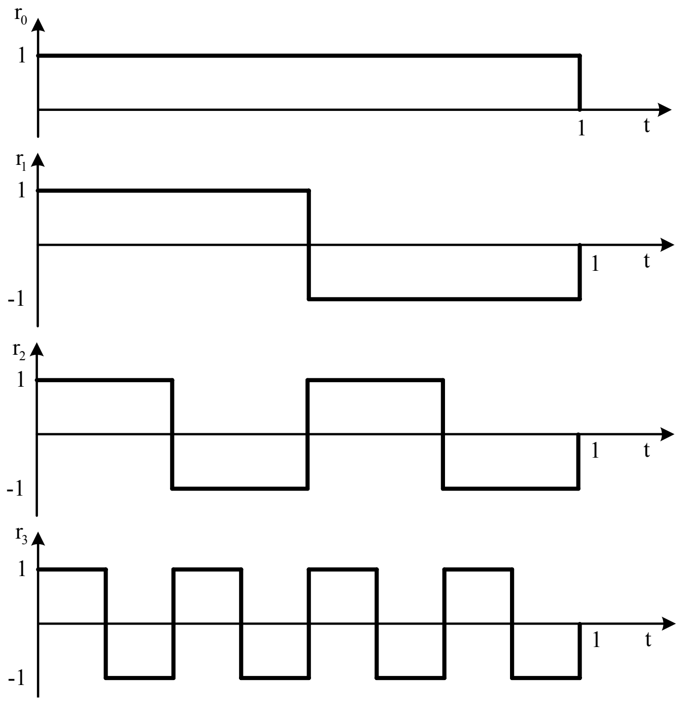

Fig. 1. The system of orthonormal Rademakher functions

The system of Walsh functions is similar to Rademakher functions and is also brought out of them, but it is a full system of orthonormal functions, that is any absolutely integrated function in the range of [0,1] can be presented with the set accuracy in the form of the weighed sum of finite number of Walsh functions. Between Walsh functions $W_i(t)$ and Rademakher functions $r_i(t)$:

$$W_0(t) = r_0(t),$$
$$W_1(t) = r_1(t),$$
$$W_2(t) = (r_2(t))^1 (r_1(t))^0,$$
$$W_3(t) = (r_2(t))^1 (r_1(t))^1,$$
$$W_4(t) = (r_3(t))^1 (r_2(t))^0 (r_1(t))^0,$$
$$W_5(t) = (r_3(t))^1 (r_2(t))^0 (r_1(t))^1,$$
$$...........$$
$$W_n(t) = (r_q(t))^{\alpha} (r_{q-1}(t))^{\beta} (r_{q-2}(t))^{\gamma} \cdot ...$$

Where $q = \text{int}(\log_2 n) + 1$,
where int means capture of the biggest integer in *N*;

$$2^{q-1}\alpha + 2^{q-2}\beta + 2^{q-3}\gamma + ... = n,$$

that is α, β, γ . — binary decomposition of number n .

The first five members of system of orthonormal Walsh functions are presented in Fig. 2.

Identification method on orthogonal Walsh functions

This method is a method of passive identification. Here the impulsive admittance function (IAF) $\omega(\tau)$ of GTE is presented in the form:

$$\omega(\tau) = \sum_{i=0}^{n} a_i W_i(\tau), \ \tau \in [0; T), \tag{1}$$

where T — interval of Walsh functions determination.

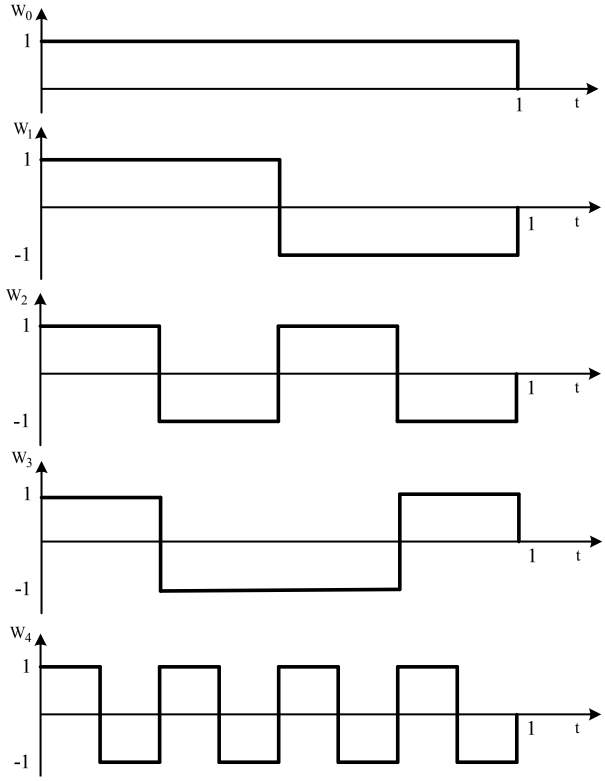

Fig. 2. The system of orthonormal Walsh functions

The interval of Walsh functions determination T is chosen by big or equal to the effective duration of IAF. The output signal $y^*(t)$ is calculated on model (1), and is defined by expression of convolution.

$$y^*(t)=\sum_{i=0}^{n} a_i \int_0^T W_i(\tau)x(t-\tau)d\tau .$$

We define a mean-square error ε^2 of a mismatch of the measured $y(t)$ and model $y^*(t)$ signals:

$$\varepsilon^2=\frac{1}{L}\int_0^L\left[y(t)-y^*(t)\right]^2 dt = \\ =\frac{1}{L}\int_0^L\left[y(t)-\sum_{i=0}^{n} a_i\int_0^T W_i(\tau)x(t-\tau)d\tau\right]^2 dt, \quad (2)$$

where L — duration of supervision interval.

We define expansion coefficients a_i from a minimum of expression (2):

$$\frac{\partial\varepsilon^2}{\partial a_j}=0 \quad j=\overline{0,n} . \quad (3)$$

Differentiating (2) and substituting in (3) we get a system of linear equations to determine a_i:

$$\sum_{i=0}^{n} a_i\int_0^L K_j(t)K_i(t)dt=\int_0^L y(t)K_j(t)dt ,\ j=\overline{0,n} ; \quad (4)$$

$$K_i(t)=\int_0^T W_i(\tau)x(t-\tau)d\tau ;$$

$$K_j(t)=\int_0^T W_j(\theta)x(t-\theta)d\theta .$$

For discrete values $x(t)$ and $y(t)$, measuring with a sampling frequency Δ the system of the equations (4) can be given to a form [1, p. 219]:

$$\sum_{i=0}^{n} a_i c_{ij}=b_j ,\ j=\overline{0,n} . \quad (5)$$

Coefficients c_{ij} and b_j are calculated on formulas ($j=\overline{0,n}$):

$$b_j=\Delta\sum_{k=1}^{L/\Delta} y^*(k\Delta)K_j(k\Delta);$$

$$c_{ij}=\Delta\sum_{k=1}^{L/\Delta} K_i(k\Delta)K_j(k\Delta);\ i=\overline{0,n} ; \quad (6)$$

$$K_j(k\Delta)=\Delta\sum_{s=1}^{T/\Delta} W_j(s\Delta)x(k\Delta-s\Delta) ;\ k=\overline{1,L/\Delta} .$$

The sampling period Δ according to Kotelnikov theorem is defined by the extreme frequency of a transmission of GTE, that is $\Delta=1/f_{\lim}$. In practice $f_{\lim}$ is often unknown. In this case value Δ can be estimated approximately as [1, p. 220]

$$\Delta=\frac{T_{\min}}{(5...10)},$$

where $T_{\min}$ – the minimum expected time constant of the object.

The choice of optimum decisive rules is firstly defined by available aprioristic and a posteriori information. We will consider available a posteriori information as coefficients of decomposition of IAF which are only identified in a series of Walsh functions $\{a_j\}$. In real systems of automatic control of GTE other information which depends on particular system is available. We designate, a priori information which is necessary in any case through the alphabet situations $\{D_i\}$. We consider various options of recognition of a situation in GTE depending on the volume of aprioristic information.

We will analyse a case when only the directions of values replacement of decomposition coefficients of IAF are known upon transition from normal operation to a surge.

Then application of rather simple procedure of diagnostics based on the analysis of a sign of a deviation of controlled parameter from nominal rate is possible.

At the same time for reliability increase of diagnostics it is expedient to allocate intervals $(a_j^0 - \varepsilon_j, a_j^0 + \varepsilon_j)$ for each decomposition coefficient a_j with nominal rate a_j^0 and definition error ε_j.

We will code a case $a_j \in (a_j^0 - \varepsilon_j, a_j^0 + \varepsilon_j)$ of 0, a case $a_j < a_j^0 - \varepsilon_j$ of –1, and a case $a_j > a_j^0 + \varepsilon_j$ – of +1.

Information on behavior of decomposition coefficients in various situations is in a table of situations, in which columns correspond to all possible situations, and lines — to all decomposition coefficients. In the corresponding cages by the provided rule are put down 0, + 1 or – 1.

In a case when values of decomposition coefficients in all situations are known, each the diagnosed condition of system can be presented in the form $(n+1)$ — dimensional vector A with components $\{a_{j0}, a_{j1}, ..., a_{jn}\}$.

The problem of situation classification $\{D_i\}$ in this case is formulated as follows: it is necessary to refer a set of decomposition coefficients, shown to one of situations established in advance.

In a case when there is sufficient statistical information: aprioristic probability of situations $P(D_i)$ the conditional density of signs values $f(a_j / D_i)$ and these distributions are unimodular, the use of statistical methods of detection, for example a statistical method of the minimum risk is expedient.

Algorithm and identification device of a surge Accepting, as a diagnostic sign of a surge decomposition coefficients in a row on Walsh functions of the studied process at the fixed interval it is possible to formulate algorithm of identification as following:

1. The measured value of process is entered y_j *.

2. On these values and $(2^n - 1)$ the previous value of process the current values of decomposition coefficients are calculated according to (5).

3. The recognition of a surge is carried out by comparison of the current decomposition coefficients with reference one.

The situation is considered found if the difference module between the current values of decomposition coefficients and the corresponding reference values doesn't exceed the set value - a threshold of the recognition determined at a stage of formation of signs by dispersion of decomposition coefficients for various realization of processes in one situation and identification errors.

In Fig. 3 the function chart of the identification device of a surge which realizes the shown algorithm is given.

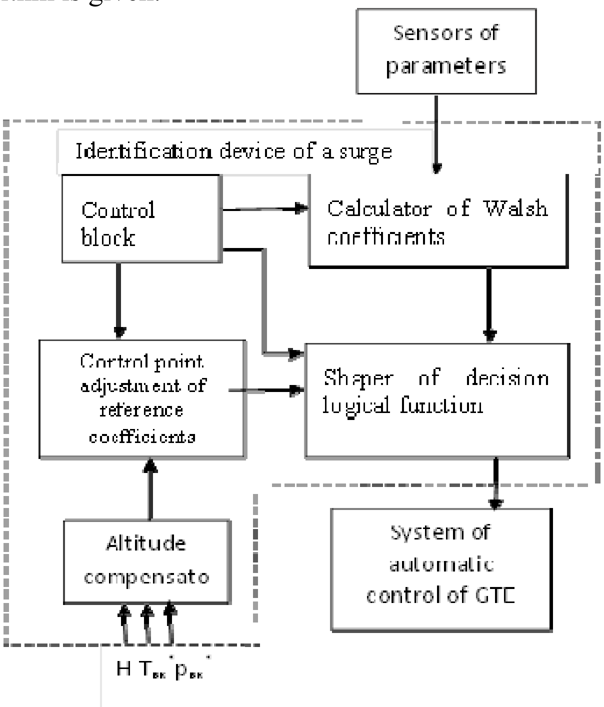

Fig. 3. Device of identification of a surge

For Walsh functions evaluation $W_i(t)$ in a time-point $t \in [0, 1]$ it is possible to use expression [5, p. 225]:

$$W_i(t) = \begin{cases} +1, \text{ якщо } S_{i1} \oplus S_{i2} \oplus ... \oplus S_{ik} = 0, \\ -1, \text{ якщо } S_{i1} \oplus S_{i2} \oplus ... \oplus S_{ik} = 1, \end{cases}$$

where S_{ir} — categories in which at binary disintegration i and t at the same time there are units; the sign $\oplus$ means addition on the module 2.

Procedure of calculation of Walsh - Fourier coefficients is rather realized on elements of digital equipment [5, p. 226].

Here decomposition coefficients of a constant sign signal are calculated

$$f^*(t) = f(t) + C \geq 0,$$

where $C = \text{const}$, which for $i \neq 0$ are Walsh — Fourier coefficients of sign (function) $f(t)$.

Definition of transitional function on the known model doesn't cause complications and on preliminary expression the simple and effective algorithm of determination of decomposition coefficients $a_i^*(P)$ at the set vector of parameters of model *P* is built. The model parameters corresponding to the IAF with decomposition coefficients a_i are determined from the condition of minimization of quadratic functional:

$$Q(P) = \sum_{i=o}^{n} [a_i - a_i(P)]^2.$$

For determination of the minimum value $Q(P)$ it is possible to use one of indirect methods of search of an extremum. Initial approach P^0 can be received by means of estimation methods by IAF, restored on the set decomposition coefficients a_i . The iterative cycle of search of a minimum begins with systematic search on *r* to the orthogonal directions (*r* — dimension of a vector P) of serial change vector components P_i at a value of a trial step $\pm h$, which in the course of search can decrease. If during iteration improvement of functional $Q(P)$ is received, then the direction of descent in the form of a vector gradient *G* which value of components q_i undertakes proportional degree improvement of functional in the corresponding directions is defined.

Conclusion

As a result of the carried researches the possibility of application of the identification method based on orthogonal decomposition of pulse transitional function in a row of Walsh functions is specified.

The algorithm and the scheme of the identification device of a surge, in which as a diagnostic sign the decomposition coefficients on Walsh functions are accepted, are developed. Formation of classes is carried out on the basis of the analysis of a large number of experimental curves of parameters change of working process at a surge and normal engine run.

REFERENCES

1. **Васильев В. И.** Автоматический контроль и диагностика систем управления силовыми установками летательных аппаратов. Москва, 1989. 240 с.

2. **Панін В. В.,** Єнчев С. В. Аналіз методів побудови систем протипомпажного захисту авіаційних газотурбінних двигунів. *Інтелектуальні системи прийняття рішень і проблеми обчислювального інтелекту*: матеріали міжн. наук. конф. ISDMCI-2010 (Херсон, 17–21 травня 2010 р.). Херсон: ХНТУ, 2010. С. 502–505.

3. **Панин В. В.,** Енчев С. В., Волянская Л. Г. Использование ортогональных разложений в задачах идентификации помпажных явлений в компрессорах авиационных газотурбинных двигателей. *Авиационно-космическая техника и технология*. 2010. №8(75). С. 112–116.

4. **Волянська Л. Г.,** Панін В. В., Гаоюн С. Методи і засоби підвищення газодинамічної стійкості компресорів газотурбінних двигунів: монографія. Київ, 2005. 200 с.

5. **Васильев В. И.** Многоуровневое управление динамическими объектами: монография. Москва, 1987. 309 с.

6. **Єнчев С. В.,** Павелко О. В. Динамічний синтез лінійної двомірної системи регулювання гвинтовентиляторів ТГВД Д-27. *Наукоємні технології*. 2010. №4(16). С. 14–19.

Олалі Н. В., Олалі М. О.

ПРИСТРІЙ-ІДЕНТИФІКАТОР ПОМПАЖУ В КОМПРЕСОРАХ АВІАЦІЙНИХ ГАЗОТУРБІННИХ ДВИГУНІВ

У статті розглядається проблема ідентифікації помпажних явищ в компресорах авіаційних газотурбінних двигунах. Для збільшення запасів стійкості двигунів використовують: регулювання направляючих апаратів компресора, перепускання повітря з окремих ступенів компресора, регульоване дозування подачі палива на режимах запуску, прийомистості, дроселювання. Ці заходи зменшують ймовірність виникнення помпажних явищ, але не можуть служити гарантією їх усунення, оскільки помпаж може бути наслідком відмов в самих системах, призначених для попередження зривів. Ефективність застосування таких систем суттєво залежить від методу ідентифікації закладеної в її принцип дії. В зв'язку з цим особливий інтерес представляє метод ідентифікації, що використовує ортогональний розклад імпульсних перехідних функцій в ряд по функціях Уолша. Обґрунтовується застосовність методу розпізнавання помпажу за допомогою розкладу імпульсної перехідної функції двигуна в ряд ортонормованих функцій Уолша. В якості діагностичної ознаки помпажу прийняті коефіцієнти розкладання Уолша - Фур'є. Розроблено алгоритм і функціональна схема пристрою ідентифікації помпажа. Формування класів проводиться на основі аналізу великої кількості експериментальних кривих зміни параметрів робочого процесу при помпажі і нормальній роботі двигуна. В результаті проведених досліджень показана можливість застосування методу ідентифікації заснованого на ортогональному розкладі імпульсної перехідної функції в ряд за функціями Уолша.

Розроблений алгоритм і схема пристрою ідентифікації помпажу, в якому як діагностична ознака прийняті коефіцієнти розкладу по функціях Уолша. Формування класів проводиться на основі аналізу великої кількості експериментальних кривих зміни параметрів робочого процесу при помпажу і нормальній роботі двигуна.

Ключові слова: помпаж; авіаційний газотурбінний двигун; пристрій ідентифікації; функції Уолша; ортогональний розклад, алгоритм.

Olali N. V., Olali M. O.

THE SURGE IDENTIFYING DEVICE IN COMPRESSORS OF AVIATION GAS-TURBINE ENGINES

This paper concentrates on the problem of identification of surge phenomena in compressors of aviation gas-turbine engines. Applicability of a surge detection method using expansion impulse response of the engine in a series of orthonormal Walsh functions is proved. As a diagnostic sign of a surge the Walsh - Fourier coefficients are accepted. The algorithm and the functional chart of the identification device of a surge are developed. Formation of classes is carried out on the basis of the analysis of a large number of experimental curves of change of parameters in workflow at a surge and normal operation of the engine.

Keywords: surge; aviation gas-turbine engine; identification device; Walsh functions; orthogonal decomposition; algorithm.

Олали Н. В., Олали М. О.

УСТРОЙСТВО-ИДЕНТИФИКАТОР ПОМПАЖА В КОМПРЕССОРАХ АВИАЦИОННЫХ ГАЗОТУРБИННЫХ ДВИГАТЕЛЕЙ

В статье рассматривается проблема идентификации помпажных явлений в компрессорах авиационных газотурбинных двигателей. Обосновывается применимость метода распознавания помпажа с помощью разложения импульсной переходной функции двигателя в ряд ортонормированных функций Уолша. В качестве диагностического признака помпажа приняты коэффициенты разложения Уолша - Фурье. Разработано алгоритм и функциональная схема устройства идентификации помпажа. Формирование классов проводится на основе анализа большого количества экспериментальных кривых изменения параметров рабочего процесса при помпаже и нормальной работе двигателя.

Ключевые слова: помпаж; авиационный газотурбинный двигатель; устройство идентификации; функции Уолша; ортогональное разложение; алгоритм.

Стаття надійшла до редакції 19.09.2018 р.
Прийнято до друку 05.12.2018 р.